Vehicular Cabins' Thermal Comfort Zones; Fanger and Berkley Modeling

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Abstract

This manuscript discusses the development of the thermal comfort zones, during summer and winter periods, inside vehicular cabins. This is done using two thermal modeling approaches; specifically Berkeley and Fanger computations. The limiting boundaries of the thermal comfort zone when computed by the Berkeley model is determined by the Overall thermal Sensation (OS ± 0.5), while according to Fanger model, the zone is determined by the Predicted Mean Vote index (PMV ± 0.5). The Berkeley simulation uses a virtual thermal manikin to predict the thermal sensation and comfort inside the cabin under different environmental conditions, while maintaining the cabin homogeneous state over a relative humidity range of (20-60%). The manikin clothing reflects the summer period through; short sleeve with long trousers at an approximate clothing insulation value of 0.5 clo. Additionally, the winter clothing for winter is long thick sleeve, long thick trousers, hand-wear and footwear with approximate clothing insulation value of 1 clo. The metabolic rate for a human passenger is set at 1.4 met to represent a seated human activity level. The same conditions are also used for the Fanger model except the range of relative humidity, which is (20-80%). The results show that the lower and upper temperature limits for the summer comfort window are at standard conditions of 22.4 and 27.3°C for the Berkeley model and at 23.1 and 27.4 °C for the Fanger model. On the other hand, the temperature limits for the winter comfort window are at 19.8 and 25.2°C for the Berkeley model and at 18.6 and 24.6 °C for the Fanger model. Additionally, the proposed study conducted a sensitivity analysis of these windows by changing (increase/decrease) of the metabolism, the cabin air velocity, and the clothing insulation values.

Keywords

Comfort Zone; Thermal Sensation; Berkeley Model; Fanger Model; Metabolic Rate; Clothing Insulation

Introduction

Comfort zones describe the specific combinations of temperature and relative humidity (RH) ranges, where 80% of the tested population felt thermally comfortable, based on statistical tests surveys (ASHRAE Standard 62, 2001). The exact delineation of the winter and summer comfort windows inside vehicular cabins assists the engineering design in selecting the most efficient means to air temper the cabin environment in response to outside conditions. The two primary steps that are required to develop such thermal comfort zones for passenger compartments can be summarized usefully by; (i) determining the main heating and cooling sources in addition to the relative humidity inside the cabin. (ii) Specifying the main characteristics of the cabin environment, which include glazing, interior materials and geometries, in addition to understanding the fast transient and in-homogenous conditions associated with such cabins.

In regard to the first step; the passenger compartment possess different sources of heat; mainly radiation based heating. Radiation can come from the cabin outside surroundings (including, external objects and the road surface); from the solar flux which is further magnified due to the green-house effect inside the cabin. Also, the vehicle powertrain and driveline components such as the engine, transmission, and the exhaust system all radiate a large amount of heat into the passenger compartment. Other minor heat contributions can come from the occupants' thermoregulatory system and the in-cabin electronics and infotainment systems. In terms of the relative humidity sources that are mainly tied to the outside humidity and the heating and/or cooling effects from the cabin AC system, because of the relative humidity dependence on the cabin Dry Bulb Temperature DBT. Also, the vehicle passengers can add considerable moisture to the cabin space through exhaled air which can be counted at 100% relative humidity. All of these sources add to the uncomfortable feeling within the passenger compartment of a vehicle. This step will assist in the exact determination of the cabin's boundary conditions for the Berkley simulation.

The next step is to identify the unique attributes of the vehicular cabins thermal behavior; in more words; the specifics of the cabin fast transient behavior and the non-uniformities associated with the cabin thermal environment due to the air temperature distribution, the solar flux, and the radiation heat flux from the cabin surrounding interior-trim surfaces. Furthermore, this step should also recognize the multiple governing parameters that control such variables such as the solar incidence angle, the glass/glazing properties, the surrounding radiant heat and air velocity, which will have a direct impact on the AC system performance (Alahmer et al., 2011; Cisternino, 1999). Additional complications are due to the psychological as well as physiological differences that exist among the passengers in addition to the variation in their thermal loads (i.e. thermal sensation, clothing, number of passengers, metabolism rate, etc.). So, the proposed study will include such variables in the simulation environment and allow the user to manipulate the exact conditions to reflect the standard case study and any possible variations.

Most of thermal comfort zone studies have been concerned on the in-door environments of static enclosures for example buildings and homes. The thermal comfort windows for such buildings are found to be rather wide due to its homogenous nature and predictable variables (Honeywell, 1997; Stipanuk, 2002); numerically, the winter comfort zone is between 20 ºC with 90% RH and 24 ºC with 25% RH. The summer conditions are between 23 ºC with 90% RH to 27 ºC with 25% RH. The American Society of Heating, Refrigerating and Air-Conditioning Engineers ASHRAE standard 55-2004 has an upper limit for humidity ratio of 0.012. This translates approximately to a relative humidity of 75% at a dry bulb temperature of 21°C and 53% at 27°C (ASHRAE standard 55, 2004). The thermal comfort conditions per the ASHRAE standard 55 (1992) during summer and winter comfort zones are depicted in Fig. 1 (ASHRAE standard 55, 1992; Sensirion Co., 2013). An alternative standard for defining the comfort zone is the ISO 7730, with its upper and lower temperature limits being vertical. This standard can be used in less demanding applications or for simpler implementation of air-conditioning algorithms. While simple temperature ranges are given per season, the relative humidity is set between 30% RH and 70% RH in winter and summer times, respectively as displayed in Fig. 2. The limits are set to decrease the risk of unpleasantly wet or dry skin, eye irritation, static electricity, microbial growth and respiratory diseases (Sensirion Co., 2013; ISO 7730, 2005).

Following paragraph provide more specific studies that addressed the thermal comfort window and range under different conditions.

Tsutsumi et al. (2002) tested the effect of low humidity on thermal comfort using a survey type study for participants under stable conditions during the summer months. Yamtraipat et al. (2005, 2006) conducted a study of the thermal comfort standards in air-conditioned buildings in Thailand and found that the thermal comfort standards are at a temperature of 26 □ C and a relative humidity of 60%, with an air velocity of 0.2 m/s. The influence of high humidity levels on the human comfort; specifically the response of sedentary human to high humidity exposure (RH between 60% - 90%) at a temperature range of 20– 2 □ C had been investigated by Fountain et al. in (1999). This study explored the RH effect qualitatively without quantifying its dependency on DBT and other conditions. Ibamoto et al. (2001) reported that low humidity levels can be accommodated in both transient and steady state conditions. More specific studies for the vehicular cabins' comfort windows are done by T. Lin et al. (2010), where he showed that the neutral temperatures for short- and long-haul vehicles are between 26.2°C and 27.4°C, while the comfort zones are 22.4–28.9°C and 22.4–30.1°C, respectively. Also, Da Silva et al. (2006) performed a survey on a 28 pre-arranged subjects onboard a bus, the results of the survey were analyzed through an artificial neural network to describe how the subjects' thermal sensations were affected by that physical environment conditions. However, these reported studies are limited number in terms of actual cabin conditions and the aforementioned specifics from steps one and two.

This manuscript investigates the passenger thermal comfort zones during both the summer and the winter periods, while taken the multitudes of governing variables into consideration. The study starts by discussing the human thermal comfort in section two; with its sub-sections introducing the Fanger and the Berkeley models. Section three elaborates on the proposed research methodology, and section four specifies the design consideration in terms of the dry bulb temperature and the relative humidity. In section five, the results of summer and winter thermal comfort zones in standard conditions, in addition to a sensitivity analysis are presented and discussed. Finally, section six summarizes the study approach and concludes its findings.

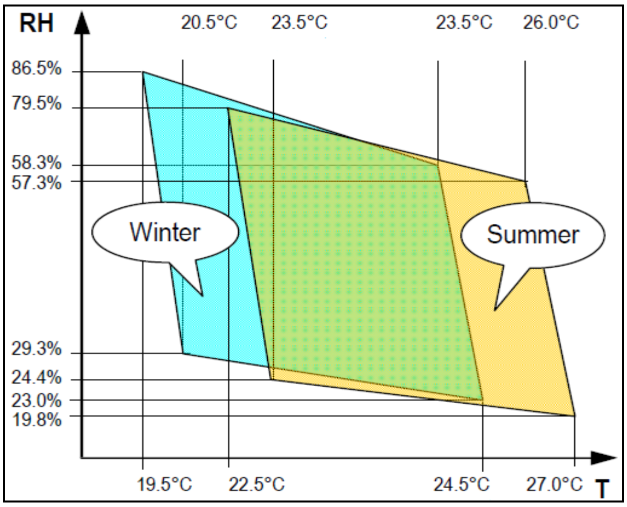

FIG. 1 RELATIVE HUMIDITY (RH) / TEMPERATURE (T) DIAGRAM BASED ON COMFORT ZONE ACCORDING TO ASHRAE 55-1992 (ASHRAE 55, 1992; SENSIRION CO., 2011)

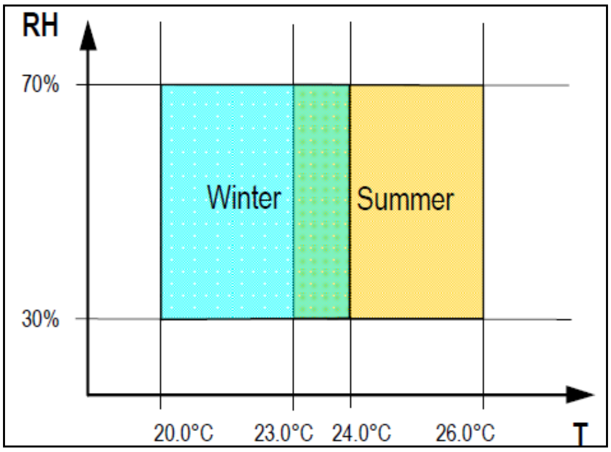

FIG. 2 RH/T DIAGRAM SHOWING THE COMFORT ZONE ACCORDING TO ISO7730 (SENSIRION CO., 2013; ISO7730, 2005)

Human Thermal Comfort Models

Human thermal comfort research approached the thermal sensation of people in their specific environments from several perspectives depending on the personal, environmental and physiological variables that influence the overall and local thermal comforts. This research resulted in mathematical models to predict and simulate the thermal response, with the most notable models being developed by P.O. Fanger (also called Fanger Comfort Model), in addition to the more recent Berkeley thermal-comfort model. These two models rely on the energy balance equation, while using the energy exchange mechanisms derived from experimental and physiological parameters, to help predict the human thermal sensation and its physiological response. On the other hand, these two approaches differ somewhat in the physiological models used to represent the human passive system (i.e. heat transfer through and from the body) and the human control system (i.e. the neural control of shivering, sweating and skin blood flow). The models also differ in the metrics used to predict thermal sensation. Following text will describe these two specific models in more details.

Fanger Model

Fanger defined the thermal comfort as "The condition of mind which expresses satisfaction with the thermal environment" (Fanger, 1970). Fanger's model is represented by the Predicted Mean Value (PMV) index that is based on the thermoregulation and the heat balance theories to help predict the thermal comfort. The PMV calculation combines four physical variables; air temperature, air velocity, mean radiant temperature, and the relative humidity; in addition to two other personal variables; the clothing insulation and the activity level. Fig. 3 depicts the Physical parameters and heat transfer modes that affect the passenger compartment (Paulke et al., 2007).

The PMV is based on a subjective seven-step scale (Charles, 2003; ISO 7730, 1994); the value of the PMV index has a range from -3 to +3, corresponding to human sensations from cold to hot, where the null value of the PMV index means neutral.

The main limitations in Fanger model are related to; its reliance on a steady state heat transfer assumptions for a panel of human subjects, also it doesn't distinguish between the local and the whole-body thermal comfort levels. The PMV also has been proposed and established for homogenous conditions only (Musat et al., 2009). These three limitations hinder the implementation of the Fanger model for vehicular cabins due to its transient, non-homogenous, and local and global attributes. However, this study will still use the Fanger index PMV because it is most standardized and used measure of thermal comfort. To overcome these limitations, the study will also implement a Berkley model simulation to complement the Fanger modelling and to better capture the specific thermal attributes of the cabins.

Berkeley Model

Berkley model provide a sophisticated thermal comfort models by using a virtual thermal manikin to represent the human thermoregulatory system in

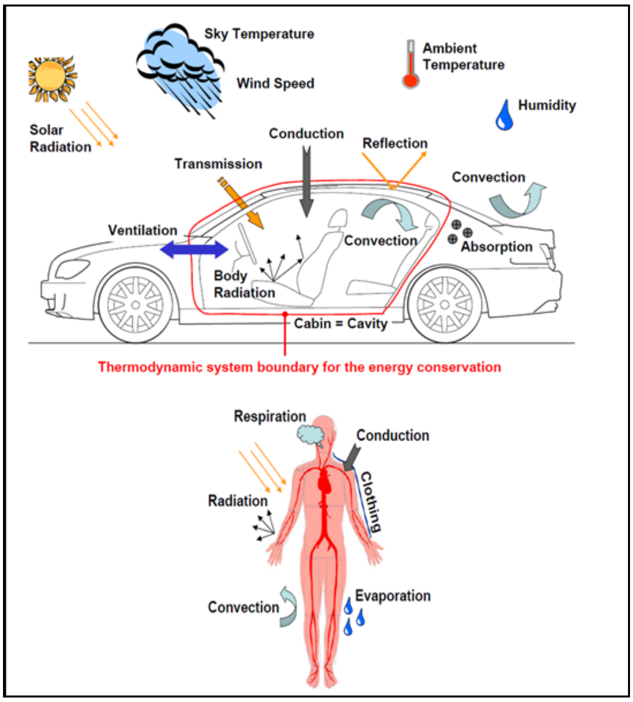

FIG. 3 PHYSICAL PARAMETERS AND HEAT TRANSFER MODES THAT EFFECT ON PASSENGER COMPARTMENT

addition to representing the local and overall sensations; all this can be done in non-uniform and transient thermal conditions.

The Berkeley Comfort Model (Zhang, 2003; Arens et al. , 2006; Zhang et al., 2010) is based on the Stolwijk model of human thermal regulation but it also includes several unique features specifically; the number of body segments included in the calculations, in addition to including a clothing layer. Also, it has the capability to capture the conduction transfer mode between and to surfaces that are in contact with the human body. The Berkley model includes an improved convection and radiation heat transfer coefficients with a radiation heat flux model (Huizenga et al., 2001). Each segment of the Berkeley manikin is modeled as four body layers (core, muscle, fat, and skin tissues) and a clothing layer; all are depicted in Fig. 4 (Paulke et al., 2007; Huizenga et al., 2001). Physiological mechanisms such as vasodilation, vasoconstriction, sweating, and metabolic heat production are explicitly considered in the model. Convection, conduction (such as to a car seat or other surfaces in contact with any part of the body) and radiation between the body and the environment are all treated independently. The model has been implemented in an object-oriented C++ computer code. It simulates an arbitrary number of sequential sets of environmental and physiological factors called phases; each phase consists of environmental and physical information such as the duration of exposure, the metabolic rate, the clothing, the physiological constants, and the external environmental factors; all of which are known to affect the human thermal comfort (Huizenga et al., 2001).

The Berkeley model uses the temperature data from the physiological model to predict the local and global thermal comforts as a function of local skin and core temperatures and their rates of change. In addition, the physiological response is used to predict the local sensation and the local comfort of each body segment. The body thermal sensation in a given environment depends on the skin temperature (cold through hot). However, the thermal comfort depends on the desired physiological state (uncomfortable through comfortable). The sensation and comfort are interrelated but their interaction is of a complex nature, which includes the environment and the dynamic physiological conditions.

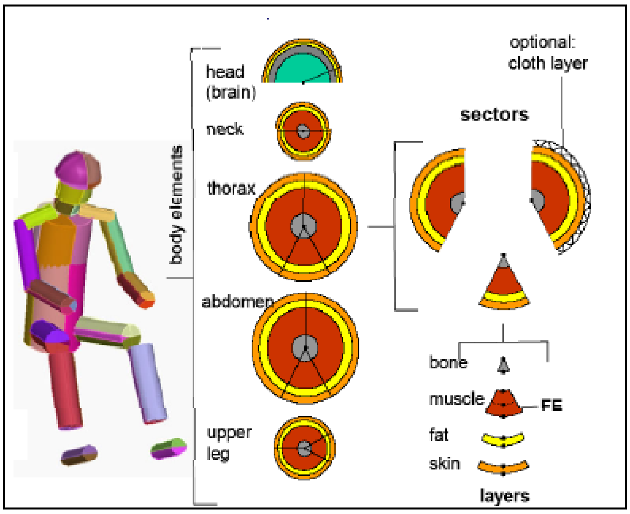

FIG. 4 HUMAN BERKELEY LAYERS (PAULKE ET AL., 2007)

Research Methodology

The aforementioned two thermal models are used to create the thermal comfort windows for the summer and winter periods; the Berkeley model using its Overall thermal Sensation (OS) value and the Fanger model using its PMV index. According to Berkeley model the virtual thermal manikin is composed of individual body parts to allow the user to define separate layers of clothing and other local effects. The environmental model used supports full weather inputs, solar models, transparent glass with greenhouse effects, and all other significant thermal variables, while the Fanger model (PMV index) requires the definition of the physical and personal parameters inside the cabin. The thermal sensation and comfort votes are then calculated using these two models. The sensation and comfort are then reported on the nine-point scale for the Berkeley model and on the seven-point thermal sensation scale for the Fanger model. On both scales, the higher positive sensation value indicates hotter feeling. On the other hand, the higher negative sensation value indicates cooler feeling, while a zero sensation indicates a neural thermal sensation. The higher comfort value indicates a better or a more comfortable feeling.

The Berkeley comfort manikin is placed inside a vehicle cabin with a homogeneous environment over a range of relative humidity of (20-60%) as shown in Fig. 5. The manikin is simulated in standard form by wearing short sleeve with long trousers with approximate clothing insulation value of 0.5 clo or 0.078 $\frac{m^2 K}{W}$ for summer period, and wearing long thick sleeve, long thick trousers, hand-wear and footwear with approximate clothing insulation value of 1 clo (0.155 $\frac{m^2 K}{W}$) for the winter period. The metabolic rate is set at 1.4 met (81 $\frac{W}{m^2}$) (Han et al., 2004; Karimi et al. , 2002) that is for a seated human metabolic rate. The measured discharge temperatures at the AC outlets are specified as the boundary conditions for the finite differencing processor. The thermal-manikin is firstly imported as a human geometry, then meshed to discretize its surface area (RadTherm 10.0.0, 2011) Then, the biological material properties and the thickness values are assigned to each individual part. The environmental boundary conditions including; the environmental variables, the clothing properties, the surface conditions, and the convection settings are all set in the model. The model then operates by solving the heat transfer balance equations using a finite differencing approach. For the Fanger model, the PMV is derived from the physics of heat transfer combined with an empirical fit to the human comfort; that is described in equation (1).

$$PMV=[\ 0.303 \exp \{ -0.036\ M+ 0.028\} \ X\ E_{st}] \qquad (1)$$

Where; M is metabolic rate of body that provides energy, E_{st} is the rate of increase of the energy stored within the human body.

Lastly, to establish the thermal comfort windows, the Berkeley overall thermal sensation (OS) inside the comfort zone or window (OS = ± 0.5) and the Fanger model thermal comfort zone (PMV= ±0.5) are computed.

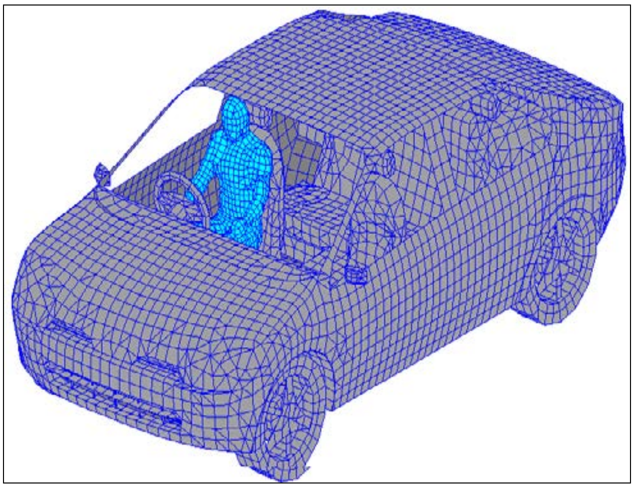

FIG. 5 SCHEMATIC OF A MANIKIN WAS PLACED INSIDE VEHICULAR CABIN UNDER A DIFFERENT ENVIRONMENTAL CONDITION

Design Considerations

The comfort zones are usually expressed graphically as an overlay on the psychometric chart or other diagrams that show the relation between temperature and relative humidity. Below text describes the different factors and their roles in manipulating the human comfort feelings.

The air temperature defined as the temperature of the air surrounding the occupant determines the net heat flow between the human body and its environment via convection. This factor is considered important because of its narrow range within the comfort zone. An increase in the temperature above the comfort level may prevent the body from dissipating its heat to the surrounding air. This will also lead to an increase in the body temperature, increased in the heart action, and a reduction in human activity performance (tired and sleepy feelings). This highlights the need to increase the compartment ventilation, induct cooler air and exhaust the hot air. On the other hand, a decrease in the air temperature may result in body shivering, reduced power to concentration and a restless feeling. So, the air temperature should be closely controlled.

Another important factor is the cabin humidity. The most body heat loss usually occurs through an evaporative process. If the air has a high RH, the potential for evaporation is greatly reduced because the air cannot easily absorb more moisture. Also, RH controls the growth and spread of unhealthy biological pollutants and microbes, in addition to the impact on cabin interior material. On the other hand, the symptoms of low relative humidity within the compartment are headache, irritated eyes, sore throat, and dry skin. At the same time, the dry air can lower the human natural defense against airborne infections making occupants more vulnerable to the attack of viruses and other micro-organisms (Ergonomic 4 school, 2011)

Typically humans are less sensitive to humidity than to temperature, so people generally fail to associate discomfort and potential health problems with variations in the relative humidity. So, it is needed to control both the relative humidity and the temperature levels to keep it within the comfort limits. Also, another advantage of controlling temperature and the RH is the potential energy can be saved when the AC system manipulate both humidity and temperature. In previous studies (Alahmer et al., 2012), the authors showed the energy savings that can be achieved if the vehicular cabins AC system controls the RH and DBT levels at the same time.

Results and Discussion

Fanger and Berkeley Models Simulation

Figs. 6 and 7 display the effect of changing the dry bulb temperature and the relative humidity on the PMV index, during summer and winter periods, with the relative humidity being on the vertical axis, and the dry bulb temperature values are on the horizontal axis; and the diagonal lines represent the PMV index values. According to the PMV index scale; humans will be thermally comfortable, if the PMV ranges from -0.5 to 0.5. At summer period, Fig. 6, occupants will be more comfortable at higher temperatures with a lower humidity. As the temperature drops, higher humidity levels are required to attain the PMV comfort range. At winter period, Fig. 7, occupants will be more comfortable at lower temperatures with a higher relative humidity. As the temperature increases, lower humidity levels are required to attain the PMV comfort range.

The prediction of the Overall Sensation (OS) during summer and winter periods according to Berkeley model at 20% RH are depicted in Figs. 8 and 9 respectively and at 60% RH are displayed in Figs. 10 and 11. The schematic of temperature variations at the boundaries of the thermal comfort zone for summer and winter periods under different relative humidity scenarios are displayed in Figs. 12 and 13, respectively. According to the Berkeley OS index scale; humans will be thermally comfortable, if the OS index ranges from -0.5 to 0.5. The data generation in Figs. 6 through 11 will be used to develop thermal comfort zone.

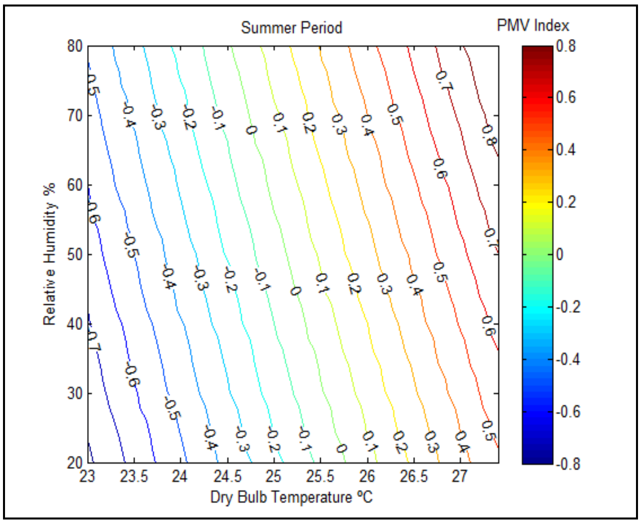

FIG. 6 EFFECT OF CHANGING RH AND DRY BULB TEMPERATURE ON PMV INDEX DURING SUMMER PERIOD (AIR VELOCITY 0.4 M/S, METABOLIC RATE 1.4 MET AND INSULATION LEVEL 0.5 CLO)

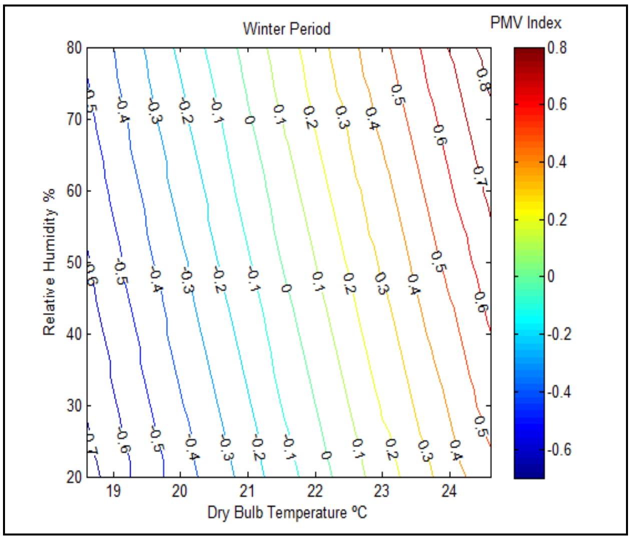

FIG. 7 EFFECT OF CHANGING RH AND DRY BULB TEMPERATURE ON PMV INDEX DURING WINTER PERIOD (AIR VELOCITY 0.4 M/S, METABOLIC RATE 1.4 MET AND INSULATION LEVEL 1 CLO)

In (Alahmer et al., 2012) the authors presented a comprehensive study the effect of manipulating the Relative Humidity (RH) along with the Dry Bulb Temperature (DBT) on vehicular cabins' environment in terms of the overall thermal comfort and human occupants' thermal sensation by using Berkeley and Fanger model. Alahmer at el. showed that the temperature variation within the cabin passes through three stages specifically; the early stage, where the thermal sensation increases rapidly in the first few minutes till it reaches a maximum value to express the human body feeling of very hot thus the human comfort decreases rapidly expressing the uncomfortable feeling due to the high surrounding temperature. During this stage, the heat is transferred from the cabin environment to the passenger body through conduction, convection and radiation. After that the overall thermal sensation starts to decrease due to the air conditioning effect which reduces the in cabin temperature. So, as time passes, the temperature of air surrounding the body decreases and the body becomes more neutral (i.e. more comfortable). In the winter period, the early stages represent a decrease in the thermal sensation in the first few minutes till it reaches a minimum value; i.e. the human body feeling of very cold. After that the overall thermal sensation starts to increase due to the air conditioning effect in increasing the air temperature surrounding the body thus and the body becomes more neutral (i.e. more comfortable), then the neutrality or thermal comfort is achieved. Additionally, (Alahmer et al., 2012) computed the temperature variation, the cabin local sensation (LS) and comfort (LC) were all analyzed for the different body segments, in addition to the overall sensation (OS) and the overall comfort (OC).

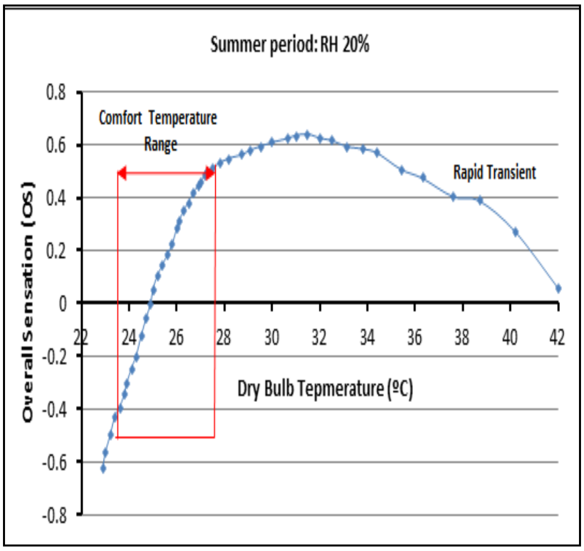

FIG. 8 PREDICTION OF OVERALL SENSATION (OS) DURING SUMMER PERIOD ACCORDING TO BERKELEY MODEL AT 20% RH

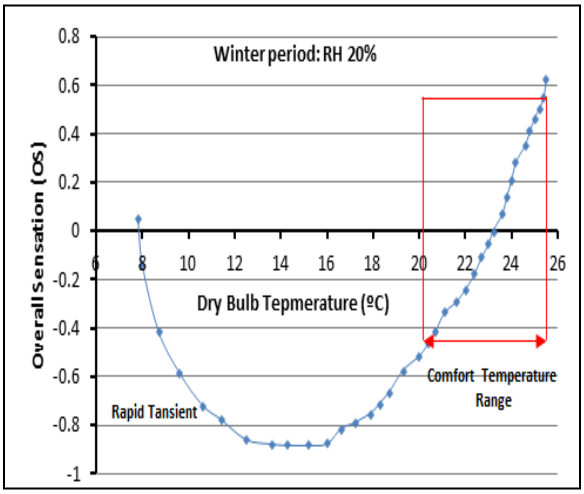

FIG. 9 PREDICTION OF OVERALL SENSATION (OS) DURING WINTER PERIOD ACCORDING TO BERKELEY MODEL AT 20% RH

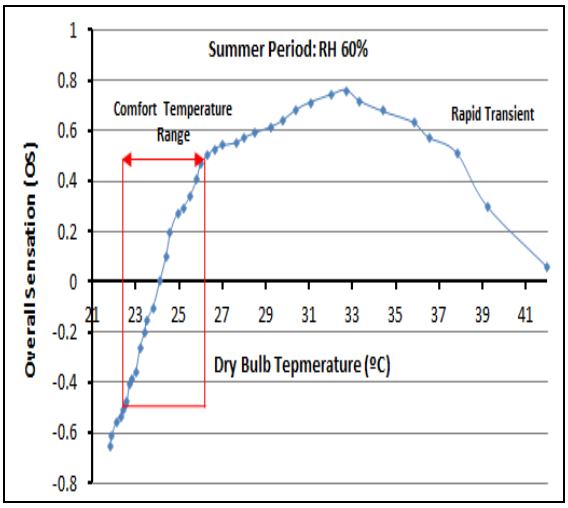

FIG. 10 PREDICTION OF OVERALL SENSATION (OS) DURING SUMMER PERIOD ACCORDING TO BERKELEY MODEL AT 60% RH

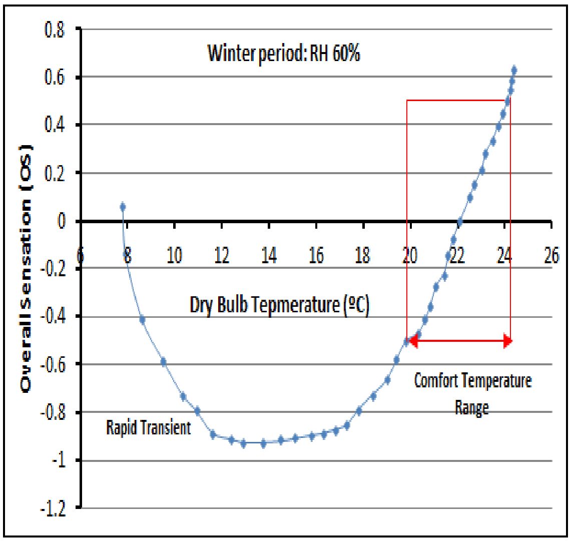

FIG. 11 PREDICTION OF OVERALL SENSATION (OS) DURING WINTER PERIOD ACCORDING TO BERKELEY MODEL AT 60% RH

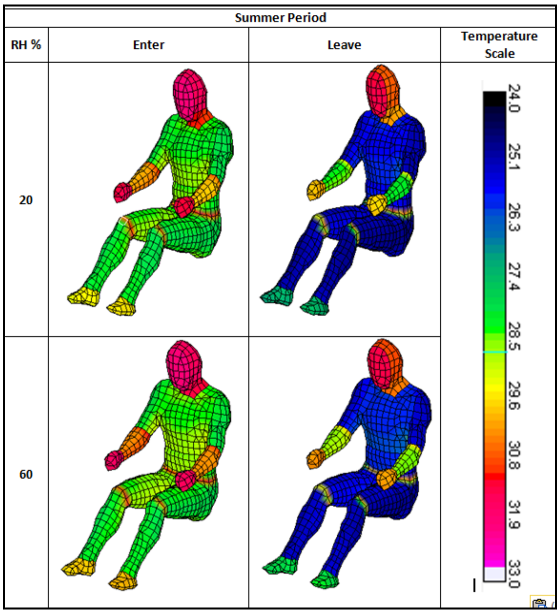

FIG. 12 SCHEMATIC OF BODY TEMPERATURE VARIATION ON IN CABIN AT ENTER AND LEAVE SUMMER THERMAL COMFORT ZONE FOR DIFFERENT RELATIVE HUMIDITY SCENARIOS

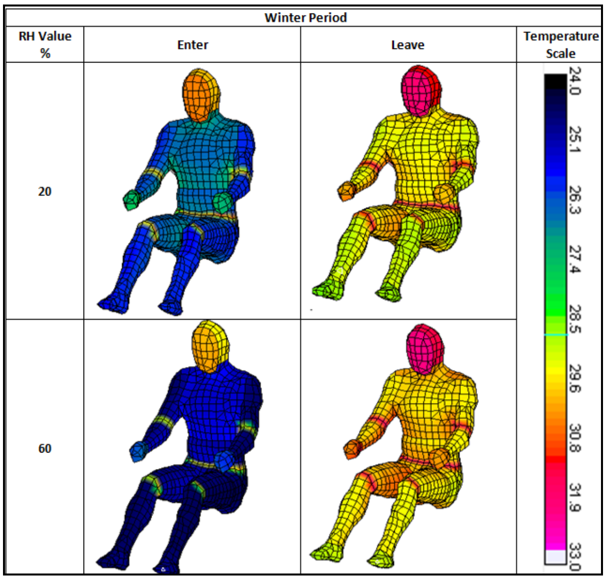

FIG. 13 SCHEMATIC OF BODY TEMPERATURE VARIATION ON IN CABIN AT ENTER AND LEAVE WINTER THERMAL COMFORT ZONE FOR DIFFERENT RELATIVE HUMIDITY SCENARIOS

Summer and Winter Passenger Thermal Comfort Zone-Standard Envelope

The comfort charts are useful pictorial design aids for controlling the passenger compartment envelope through heating, ventilation, and air conditioning (HVAC) equipment. The Fanger and Berkley models are used to design such limits for the summer and the winter comfort zones as shown in Figs. 14 and 15, respectively.

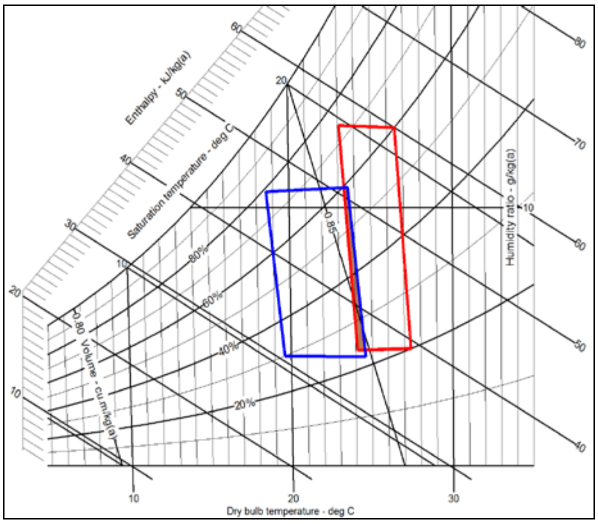

FIG. 14 SUMMER AND WINTER PASSENGER THERMAL COMFORT ZONES (SCZ-WCZ) ACCORDING TO FANGER MODEL

Two comfort windows or zones are defined by the enclosed regions on the comfort chart - one for winter and one for summer. The differences are primarily related to the variation in the clothing levels between winter and summer. The thermal conditions within these envelopes are estimated to be acceptable to 80 percent (Famger model: PMV = ± 0.5 or Berkey mode: OS=± 0.5) of the occupants when wearing the clothing ensemble indicated. To satisfy 90 percent of the people, the limits of the acceptable comfort zone are sharply reduced to one-third of the above ranges (Huamn Comfort and Health, 2011). The lower and upper temperature limits on the summer comfort window 23.1 and 27.4 °C for the Fanger model, and 22.4 and 27.3°C for the Berkeley model. While in the winter comfort window, the temperature limits are18.6 and

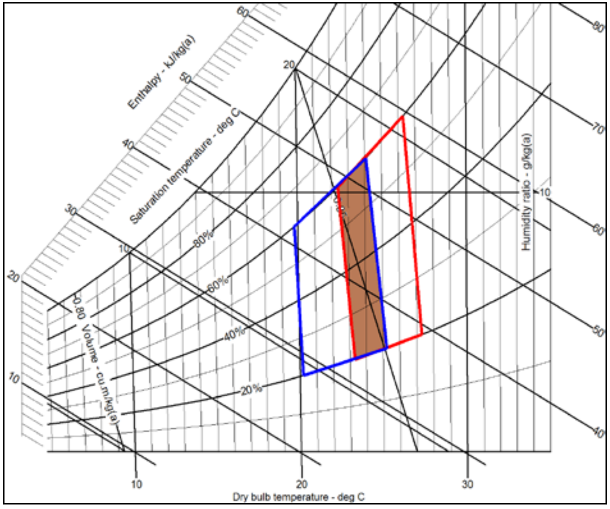

FIG. 15 SUMMER AND WINTER PASSENGER THERMAL COMFORT ZONES (SCZ-WCZ) ACCORDING TO BERKELEY MODEL

24.6 °C for the Fanger model, and 19.8 and 25.2°C for the Berkeley model.

The upper and lower humidity limits on the comfort window of above Figs. are based on maximum achieved comfort while considering the respiratory health, mold growth, and other moisture-related phenomena into consideration. Humidification in winter must be limited at times to prevent the condensation on cold windows, which might affect the visibility. The zones overlap in the 23.6 to 24.6 °C range for the Fanger model and the 23.2 to 25.2 °C. In this region, people in summer dress tend to be slightly cool, while those in winter clothing feel a slightly warm sensation.

The limitation of proposed passenger comfort window is designed to accommodate the overall comfort not specific to discrete human-body parts, in more words although a person may feel thermally neutral in general -preferring neither a warmer nor a cooler environment - thermal discomfort may exist if one part of the body is warm while another is cold.

Passenger Thermal Comfort Zones; A Sensitivity Analysis

This study will also articulate the sensitivities associated with any variations in the environmental conditions or personal factors on the proposed passenger comfort zones. This is important to show that when one of environmental conditions (dry-bulb temperature, humidity, Mean radiant temperature MRT, air movement) or personal factors (Metabolic rate and clothing) change, adjusting one or more of the other conditions can still restore the thermal comfort with minimal energy transfer (addition or subtraction). Additionally, it describes the robustness of the developed ranges from the Fanger and Berkley models.

1) *Metabolism and Activity Variations*

The effect of variations in metabolism and activity levels on the summer passenger thermal comfort zone, when computed using Fanger and Berkeley models are depicted in Figs. 16 and 17, respectively. While the effect on the winter period is displayed in Figs. 18 and 19, respectively. The metabolic rate expresses the rate of transformation of chemical energy into heat and mechanical work by metabolic activities within an organism, usually expressed in terms of unit area of the total body surface. In this standard, this rate is expressed in met units (ASHRAE Standard 55, 2004). Hence, the metabolic rate depends on the activity and the fitness levels.

When the air temperature is low, the convective heat loss increases as the air motion is associated with the increased activity, thereby decreasing the heat load on the body evaporative system and resulting in a wider range of activities before discomfort is felt. The maximum range of activity in which people feel comfortable is therefore achieved by minimizing dry-bulb temperature and the RH while compensating with a Mean Radiant Temperature MRT that is sufficient to maintain comfort. In Figs. 16 to 19, as the metabolic rate increases, the thermal comfort zone shifts to the left, which lead to a decrease in the limits of the higher and lower temperature values. So, the new lower and upper temperature limits on the summer comfort window are 21 and 26 °C for the Fanger model, and 20.8 and 25.6 °C for the Berkeley model. While the winter comfort window temperature limits are15.9 and 22.7 °C for the Fanger model, and 18 and 24 °C for the Berkeley model.

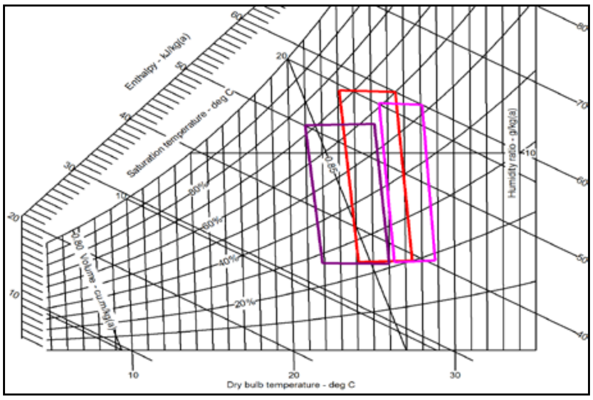

FIG. 16 METABOLISM SENSITIVITY ANALYSIS OF SUMMER PASSENGER THERMAL COMFORT ZONE ACCORDING TO FANGER MODEL

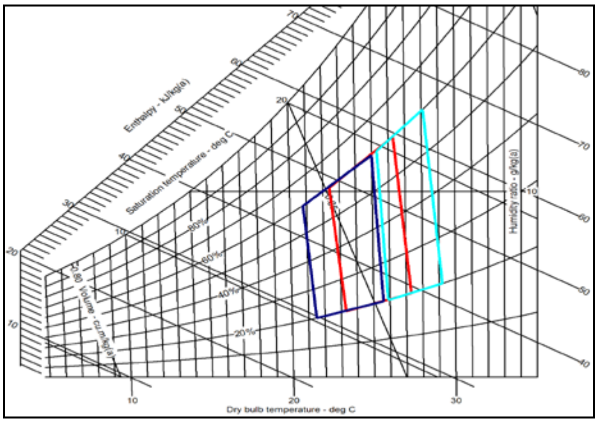

FIG. 17 METABOLISM SENSITIVITY ANALYSIS OF SUMMER PASSENGER THERMAL COMFORT ZONE ACCORDING TO BERKELEY MODEL

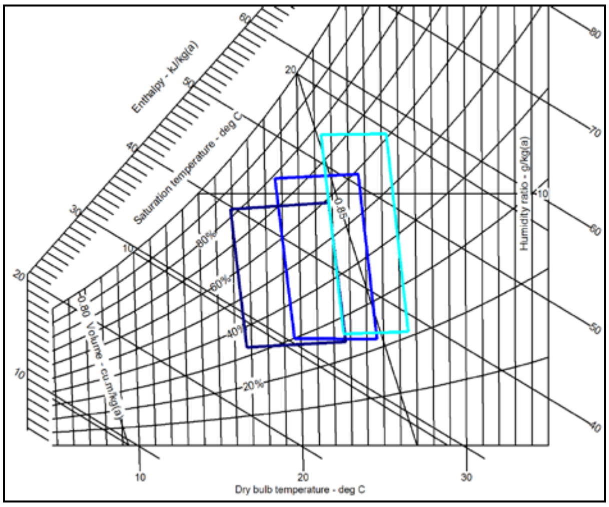

FIG. 18 METABOLISM SENSITIVITY ANALYSIS OF WINTER PASSENGER THERMAL COMFORT ZONE ACCORDING TO FANGER MODEL

So, with higher metabolic rates and/or with more clothing insulation, people are less thermally sensitive and consequently the risk of local discomfort is lower (ASHRAE Standard 55, 2004)

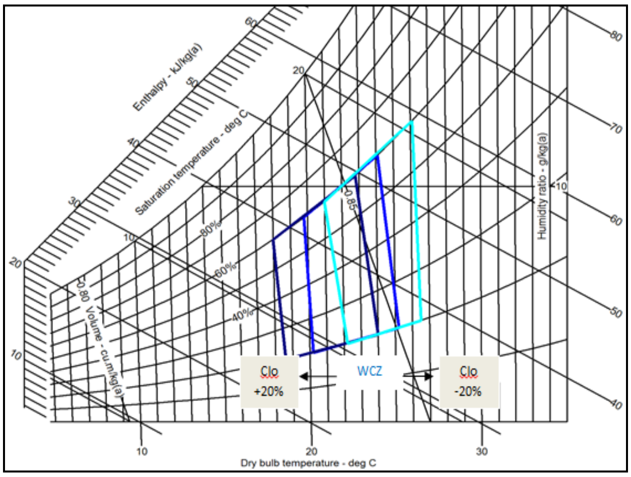

FIG. 19 METABOLISM SENSITIVITY ANALYSIS OF WINTER PASSENGER THERMAL COMFORT ZONE ACCORDING TO FANGER MODEL.

When the metabolic rate decreases, the thermal comfort zone shifts to the right, which leads to an increase in the limits of the higher and lower temperature values. So, the new lower and upper temperature limits for the summer comfort window 25.5 and 28.8 °C for the Fanger model, and 25.3 and 29.2 °C for the Berkeley model. While the winter comfort window temperature limits are 21.4 and 26.5 °C for the Fanger model, and 21 and 26.5 °C for the Berkeley model. So occupants are more sensitive to local discomforts when the whole body is cooler than neutral and less sensitive to local discomfort when the whole body is warmer than the neutral stage (ASHRAE Standard 55, 2004). As the metabolic rate increases above the limit value, the evaporation of sweat becomes a more important factor for thermal state. The Fanger model in term of its PMV calculation does not fully account for this variation.

2) *Air Velocity Sensitivity Analysis*

The sensitivity analysis associated with variations in the cabin air velocity for summer passenger thermal comfort zone according to Fanger and Berkeley models are depicted in Figs. 20 and 21, respectively. While the winter variations are displayed in Figs. 22 and 23. The air motion across the skin cools the human body through both convective energy transfer and the latent energy transfer (evaporative of perspiration from skin). When the skin temperature is relatively high, the air can carry some of the excess heat away from the body. So the air velocity, particularly if light clothing is worn, through fan settings control can provide the individual passengers more control over their local climatic environment. In Figs. 20 to 23, as the air velocity increases, the thermal comfort zone shifts to the right, this leads to an increase in the limits of the higher and lower temperature values. So, the new lower and upper temperature limits on the summer comfort window are 23.4 and 27.6 °C for Fanger model, and 22.7 and 27.6 °C for Berkeley model. While on the winter comfort window, the temperature limits are 18.9 and 24.9 °C for Fanger model, and 20.3 and 25.6 °C for Berkeley model. On the other hand, when the air velocity decreases, the thermal comfort zone shifts to the left, leading to a decrease in the limits of the higher and lower temperature values. Previous studies showed that occupant discomfort increased with increasing the air velocity, and decreasing the dry bulb temperature (Fanger, 1970).

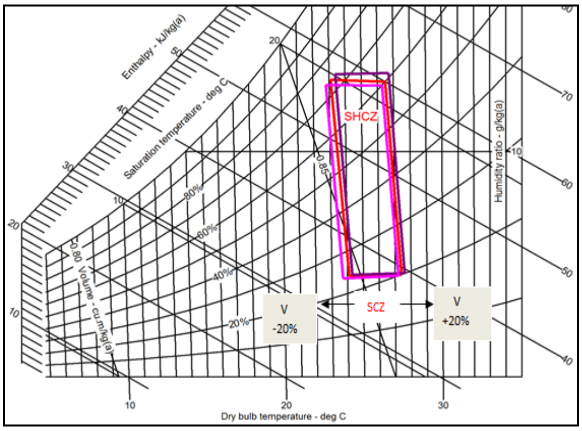

FIG. 20 AIR VELOCITY SENSITIVITY ANALYSIS OF SUMMER PASSENGER THERMAL COMFORT ZONE ACCORDING TO FANGER MODEL

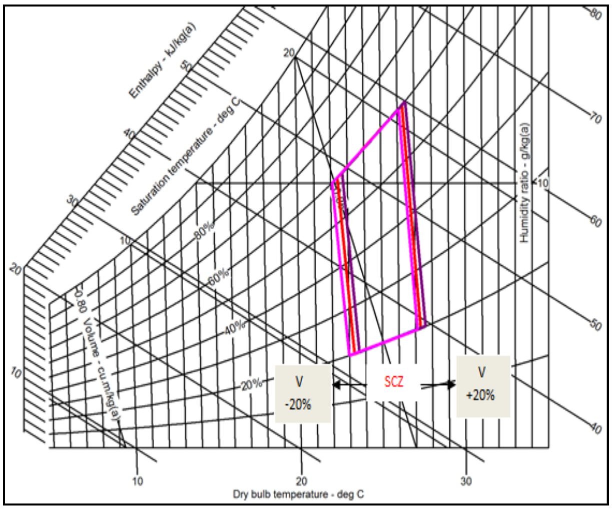

FIG. 21 AIR VELOCITY SENSITIVITY ANALYSIS OF SUMMER PASSENGER THERMAL COMFORT ZONE ACCORDING TO BERKELEY MODEL.

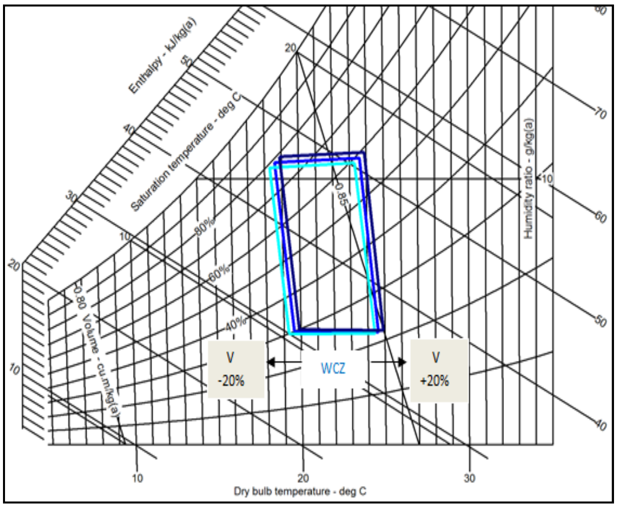

FIG. 22 AIR VELOCITY SENSITIVITY ANALYSIS OF WINTER PASSENGER THERMAL COMFORT ZONE ACCORDING TO FANGER MODEL.

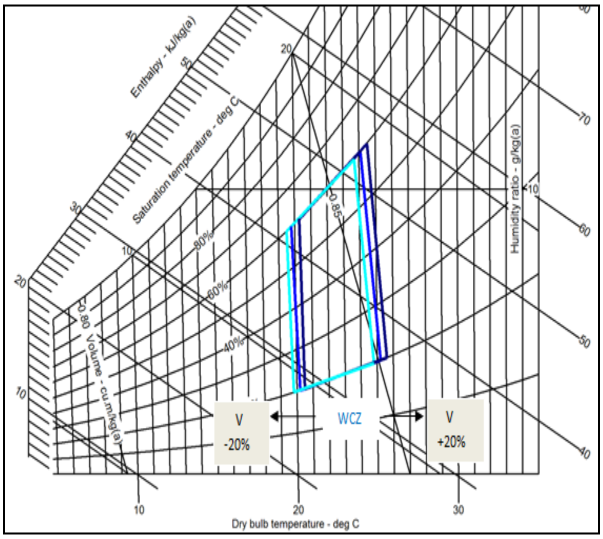

FIG. 23 AIR VELOCITY SENSITIVITY ANALYSIS OF WINTER PASSENGER THERMAL COMFORT ZONE ACCORDING TO BERKELEY MODEL.

3) *Clothing Insulation; Sensitivity Analysis*

The Clothing insulation and its effect on the summer passenger thermal comfort zone according to Fanger and Berkeley models are shown in Figs. 24 and 25, respectively. Additionally, the effect on the winter zones are exhibited in Figs. 26 and 27. During the cold weather, the layering of insulating clothes can help keep a person warm. At the same time, if the person is involved in high level of physical activity, such layers can prevent the heat loss. Generally, the thicker the garment is the greater it insulates. Depending on the type of the clothing material, the air movement and the relative humidity can decrease its insulation ability. So, all four heat transfer mechanisms namely; Evaporation, Convection, Radiation and Conduction are greatly influenced by clothing. Shoes can reduce heat loss/gain from the floor. Clothing can also prevent air movement at the skin surface, which almost eliminates the convective and the evaporative heat transfer from the skin. In Figs. 24 to 27, as the clothing or insulation level increases, the thermal comfort zone shifts to the left, leading the limits of the higher and lower temperature values to decrease. On the other hand, when the clothing or insulation level decrease, the thermal comfort zone shifts to the right. Table 1 presents a concise summary of the temperature and relative humidity limits and their variations for the cabin thermal comfort zones, under summer and winter periods, and according to the Fanger and the Berkeley models.

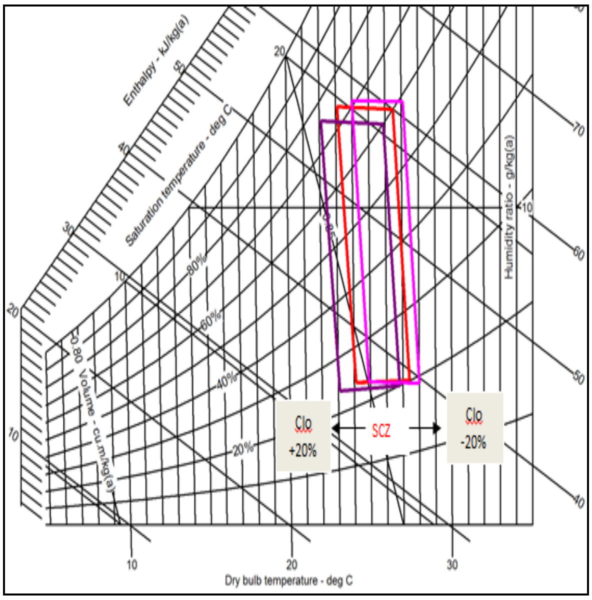

FIG. 24 CLOTHING INSULATION SENSITIVITY ANALYSIS OF SUMMER PASSENGER THERMAL COMFORT ZONE ACCORDING TO FANGER MODEL.

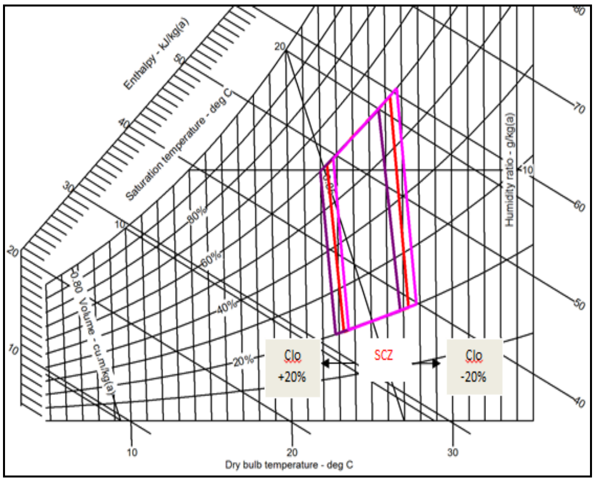

FIG. 25 CLOTHING INSULATION SENSITIVITY ANALYSIS OF SUMMER PASSENGER THERMAL COMFORT ZONE ACCORDING TO BERKELEY MODEL.

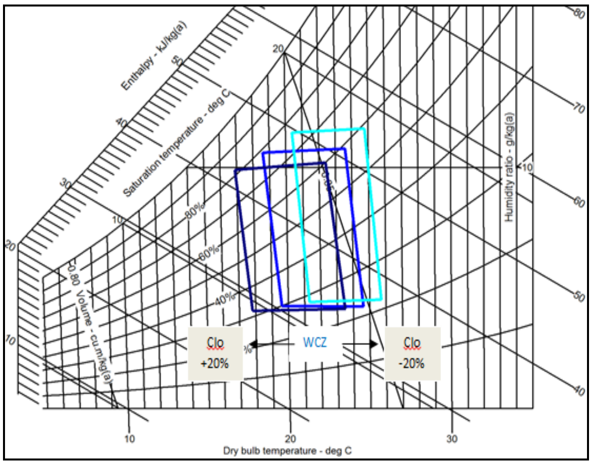

FIG. 26 CLOTHING INSULATION SENSITIVITY ANALYSIS OF WINTER PASSENGER THERMAL COMFORT ZONE ACCORDING TO FANGER MODEL.

TABLE 1 PASSENGER THERMAL COMFORT ZONE LIMITS WITH SENSITIVITY ANALYSIS FOR SUMMER AND WINTER PERIODS ACCORDING TO FANGER AND BERKELEY MODELS

	Summer Period				**Winter Period**			
	Fanger Model -PMV Index		**Berkeley Model**					
	T □ C - Range	**Rh %- Range**	**T □ C - Range**	**Rh % - Range**				
***Standard**	23.1-27.4	20-74 %	22.4-27.3	20-60 %				
****Standard**					18.6-24.6	22-79 %	19.8-25.2	20-60 %
Metabolism (+ 20%)	21-26	21-73 %	20.8-25.6	20-60 %	15.9-22.7	24-83 %	18-24	20-60 %
Metabolism (-20%)	25.5-28.8	19-61 %	25.3-29.2	20-60 %	21.4-26.5	21-77 %	21-26.5	20-60 %
Velocity (+20%)	23.4-27.6	20-74 %	22.7-27.6	20-60 %	18.9-24.9	22-79 %	20.3-25.6	20-60 %
Velocity (-20%)	22.8-27.2	20-74 %	22.1-27.1	20-60 %	18.3-24.4	22-79 %	19.5-24.8	20-60 %
Clothing (+20%)	22.1-26.8	20-76 %	22-26.8	20-60 %	16.9-23.5	23-82 %	18.8-24.6	20-60 %
Clothing (-20%)	24-28	19-71 %	22.8-27.8	20-60 %	20.4-25.7	22-76 %	20.8-26.1	20-60 %

*Metabolic rate: 1.4 met, Clothing insulation: 0.5 clo and Air velocity: 0.4m/s

**Metabolic rate: 1.4 met, Clothing insulation: 1 clo and Air velocity: 0.4m/s

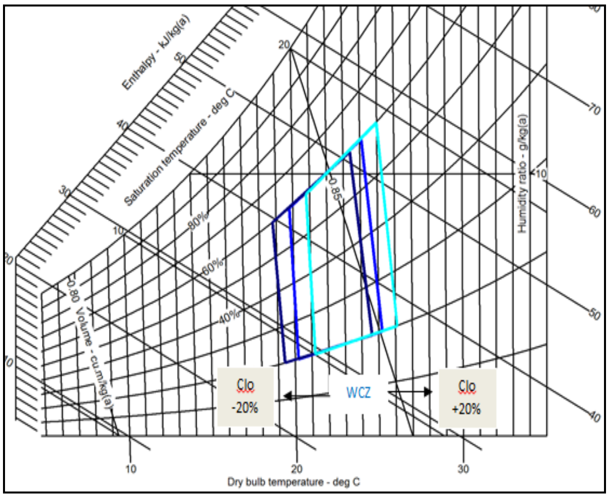

FIG. 27 CLOTHING INSULATION SENSITIVITY ANALYSIS WINTER PASSENGER THERMAL COMFORT ZONE ACCORDING TO BERKELEY MODEL.

Conclusion

This manuscript developed the passenger thermal comfort zones during the summer and the winter periods for a vehicular cabin. Two different models were used to generate the comfort windows namely; the Fanger and the Berkeley calculations. The study results can be usefully summarized into following points:

- The thermal conditions within these envelopes are estimated to be acceptable to around 80 percent (Fanger model: PMV= ±0.5or Berkely model OS = ±0.5) of the occupants when wearing the clothing ensemble indicated.
- The temperature ranges on the summer comfort window are 23.1- 27.4 °C with 20-74 % RH for the Fanger model, and 22.4 - 27.3°C

with 20-60% RH for the Berkeley model. While the winter comfort window temperature limits are18.6- 24.6 °C with 22-79% RH for the Fanger model, and 19.8- 25.2°C with 20-60% RH for the Berkeley model.

- When the metabolic rate increases, the thermal comfort zone shifts to the left, which leads to a decrease in the temperature limits (higher and lower boundaries) and vice versa.
- When the air motion across the skin surface increases, the thermal comfort zone shifts to the right, causing the temperature limits (higher and lower boundaries) to increase slightly, and vice versa.
- When the clothing insulation level increases, the thermal comfort zone shifts to the left, leading the temperature limits to decrease and vice versa.
- The thermal comfort windows generated using the Berkley model are found more robust to changes in the environmental conditions and the personal factors, than the Fanger model. Also, the Berkley model is found to better capture the local sensations than the Fanger model.

Future work includes the development of a control strategy that uses the information from this study to manipulate the cabin environment based on the passenger(s) personal factors and the cabin initial conditions.

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